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Energy Procedia 77 (2015) 546 – 550

Energy

Procedia

5th International Conference on Silicon Photovoltaics, SiliconPV 2015

Enhanced stable regeneration of high efficiency Cz PERC cells

Franziska Wolny^{a*}, Torsten Weber^a, Gerd Fischer^a, Axel Herguth^b, Svenja Wilking^b^a*SolarWorld Innovations GmbH, Berthelsdorfer Str. 111a, 09599 Freiberg, Germany*^b*University of Konstanz, Universitätsstraße 10, 78464 Konstanz, Germany*

Abstract

In this work we investigate the regeneration (permanent deactivation of light induced degradation, LID) of industrial high efficiency PERC cells. This procedure transforms the boron oxygen related defects responsible for LID into a less active state. Recently it was found that the hydrogen content in the passivation layer of boron doped Cz silicon lifetime samples plays a crucial role during regeneration. This effect is tested here on PERC cells fabricated with silicon nitride capping layers of different refractive indices and thus different compositions. We are able to confirm the results on cell level: PERC cells with high stable efficiencies of approximately 20% are achieved with an industrially applicable short regeneration step. The possibility of regeneration can be a very important factor when choosing the bulk resistivity with respect to the highest efficiency potential for PERC cells.

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Peer review by the scientific conference committee of SiliconPV 2015 under responsibility of PSE AG

Keywords: PERC; regeneration, LID

1. Introduction

The passivated emitter and rear solar cell (PERC) concept is one of the most promising new solar cell concepts currently transferred from lab scale into production [1]. In such cell concepts where the efficiency is less limited by surface recombination but rather by the bulk minority carrier lifetime, light induced degradation (LID) has a larger detrimental effect on the cell efficiency than in full area aluminium back surface field cells. The reduced lifetime caused by LID is due to the formation of boron-oxygen-related recombination centers in the silicon bulk during

* Corresponding author. Tel.: +49 3731 301 1904 ; fax: +49 3731 301 1690.

E-mail address: franziska.wolny@solarworld.com

prolonged illumination [2-4]. Consequently, a lower base resistivity and thus higher boron doping is known to increase the boron-oxygen-defect related LID [3, 5]. This is one of the main reasons that often relatively lowly doped silicon material is preferred for the production of high efficiency solar cells although a higher doping level can lead to a better cell performance prior to degradation [1].

It has been shown that the detrimental effects of LID can be reduced or even eliminated by illumination at elevated temperatures. This procedure, also known as regeneration, permanently deactivates boron-oxygen related recombination centers [6]. Regeneration in an industrial scale could expand the range of possible boron doping levels for solar cell production and open up possibilities for further PERC cell efficiency optimizations.

Recently it was found by Wilking et al. that the hydrogen content in the bulk of boron doped Cz silicon lifetime samples plays a crucial role during regeneration [7, 8]. The hydrogen content in the bulk can in turn be influenced by the composition of the passivation layer and/or the firing conditions. A $\text{SiN}_x\text{:H}$ deposition with reduced NH_3 flow leads to a less dense $\text{SiN}_x\text{:H}$ layer releasing less atomic hydrogen into the silicon bulk during a high temperature treatment [9,10]. Wilking et al. found that samples with a lower Si-N bond density in the $\text{SiN}_x\text{:H}$ passivation layer regenerate more slowly than samples with a higher Si-N bond concentration, corresponding to a higher hydrogen concentration in the bulk.

Previously, we presented results on the reduction of LID in PERC cells of varying bulk resistivity by applying a regeneration procedure at different temperatures [5]. In this work, we focus on the enhancement of the regeneration effect by changing the composition of the silicon nitride capping layer of PERC cells confirming the results of Wilking et al. on cell level. Furthermore, we test the stability of the regenerated state after illumination.

2. Experimental setup

PERC cells based on boron doped Czochralski (Cz) grown material with a base resistivity of $1.9 \pm 0.3 \Omega\text{cm}$ and an interstitial oxygen content of $(1.3 \pm 0.4) \cdot 10^{18} \text{ cm}^{-3}$ are investigated. All used PERC cells have an initial cell efficiency of 19.8% to 20.2%.

In a first experiment, the influence of the composition of the $\text{SiN}_x\text{:H}$ capping layer of the rear side passivation on the regeneration kinetics is examined. The density of the capping silicon nitride is varied by varying the monosilane to ammonia gas ratio during the CVD process as displayed in Table 1. The layer thickness is similar in all three cases. According to [7], the more the gas ratio tends towards ammonia, the higher is the mass density of the resulting $\text{SiN}_x\text{:H}$ layer. The dense layer can then release more atomic hydrogen into the silicon bulk during the firing step. The regeneration of the PERC cells of all three groups is carried out at 170°C and an illumination intensity of approximately 0.5 suns.

In a second experiment, the regeneration conditions for PERC cells with a bulk resistivity of $1 \Omega\text{cm}$ and $2 \Omega\text{cm}$ are varied. The stability of the PERC cell efficiency after regeneration with parameters applicable for an in-line process is tested [8]. This is done by illuminating the regenerated cells for 24 h at 45°C and 0.1 suns illumination. Pre-tests have shown that the cell efficiency then saturates, so this treatment should be adequate to evaluate to which extent the BO-defects are in the regenerated state.

Table 1. CVD variation of the rear side $\text{SiN}_x\text{:H}$ layer of PERC cells.

	group 1	group 2	group 3
$\text{SiH}_4 : \text{NH}_3$ ratio	1:6	1:10	1:15
Refractive index of the $\text{SiN}_x\text{:H}$ layer (@633nm)	2.21	2.09	1.99
Presumed relative hydrogen release during firing	low	medium	high

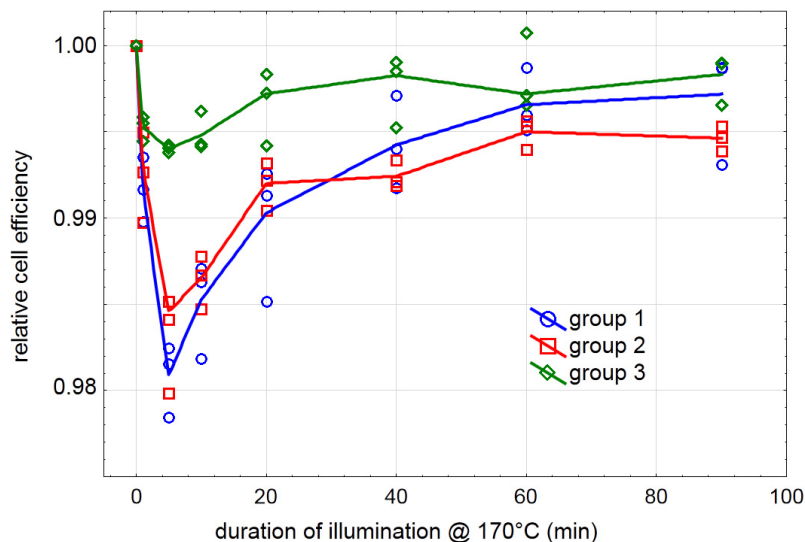


Fig. 1. Regeneration behaviour of PERC cells of groups 1-3. Each data point corresponds to one treated cell. The lines are guides to the eye.

3. Results and discussion

3.1. Influence of the PERC passivation capping layer composition on the regeneration kinetics

Figure 1 displays the regeneration behaviour of PERC cells fabricated with the CVD variations of Table 1. Starting from the as printed value, the cell efficiency drops during the first five minutes of regeneration and then slowly recovers again. Cells with a lower $\text{SiH}_4:\text{NH}_3$ ratio show a reduced efficiency drop and regenerate slightly faster. These findings match the results obtained with lifetime samples in [7] and suggest that the PERC passivation layer properties can indeed be adjusted in favour of a faster regeneration without negatively influencing the electrical performance of the cell (the three groups have a similar efficiency distribution). Also, the underlying passivation layer seems to be thin enough as not to prevent hydrogen diffusion from the $\text{SiN}_x:\text{H}$ into the silicon bulk [7]. However, the overall regeneration is quite slow in this experiment. It takes 20 to more than 60 minutes for the cells to regain 99.5% of their initial efficiency. Note that the required time could indeed be significantly reduced by applying higher temperatures and light intensities, however, monitoring and analysing the dynamics based on the characteristic progression, as observable in Figure 1, is then becoming more challenging and less instructive.

3.2. Extent of the regenerated state achieved with industrially applicable regeneration conditions

In [8] it is demonstrated that a much faster, stable regeneration can be achieved with higher temperature and light intensity. We applied these favourable conditions to the PERC cells in this experiment. Figure 2 shows the relative PERC cell efficiency after regeneration at various settings and the stability test. It can be seen that the regeneration at 130°C at 1.2 suns is the most stable, but with one hour also the slowest process. A fast and still sufficiently stable regeneration can be achieved at 220°C and 2.7 suns illumination. A regeneration time of 20s is then enough to stabilize the relative cell efficiency at 98.5% for 1 Ωcm PERC cells and 98.8% for 2 Ωcm PERC cells as compared to 94.5% and 97% without regeneration [5]. After 1 min regeneration, the stabilized cell efficiency is more than 99% of the initial annealed value. Such parameters are well suited for production cycle times, preferably with even higher light intensities and thus regeneration times of less than 20s. With the fast regeneration process, Cz with lower resistivity thus becomes increasingly interesting for high efficiency PERC cells.

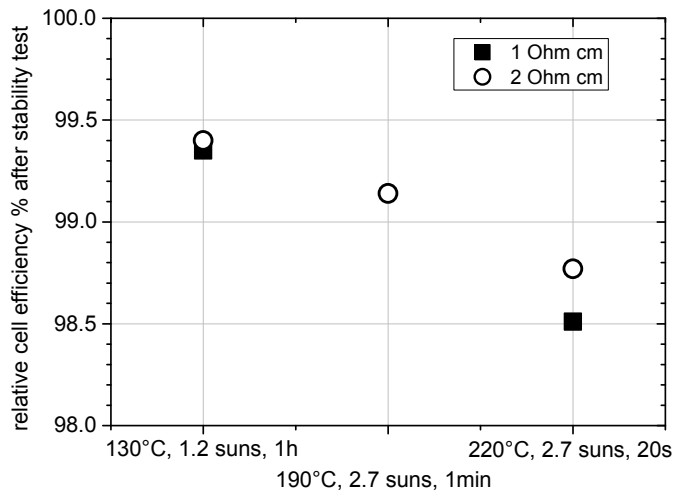


Fig. 2. Stable relative cell efficiencies after regeneration of PERC cells with 1 and 2 Ωcm bulk resistivity. The respective regeneration conditions are displayed on the bottom of the graph.

Figure 3 shows initial and stabilized absolute efficiencies of 2 Ωcm PERC cells. Four cells of similar efficiency were chosen and regenerated at various light intensities, temperatures and durations. As shown already in Figure 2, the best stable results are achieved at lower temperatures and longer regeneration durations. The equilibrium between regenerated and annealed state might be shifted towards the annealed state for higher regeneration temperatures. According to the current regeneration theory [8], this could possibly be compensated by even higher illumination intensities. For the best case in our experiment, stable efficiencies of around 20% can be achieved. This corresponds to stable module efficiencies of more than 285 W (assuming a cell to module loss of 1%).

In Figure 4, the relative change of the cell parameters after degradation, regeneration, stability test and final anneal of a typical PERC cell with 2 Ωcm bulk resistivity are displayed. As reported earlier [5], the largest degradation is seen in the fill factor due to the changed injection dependence of the excess carrier lifetime after LID. After the stability test, the cell efficiency does not degrade further as compared to the regenerated value. The final anneal is performed to check whether there occurred non-reversible degradation mechanisms not related to BO-LID. These seem to make up for 0.05% relative efficiency loss (seen equally in 4 similar cells) and do not affect the fill factor. There might be a slight degradation of the passivation or the emitter, the reasons for this permanent degradation need to be studied further.

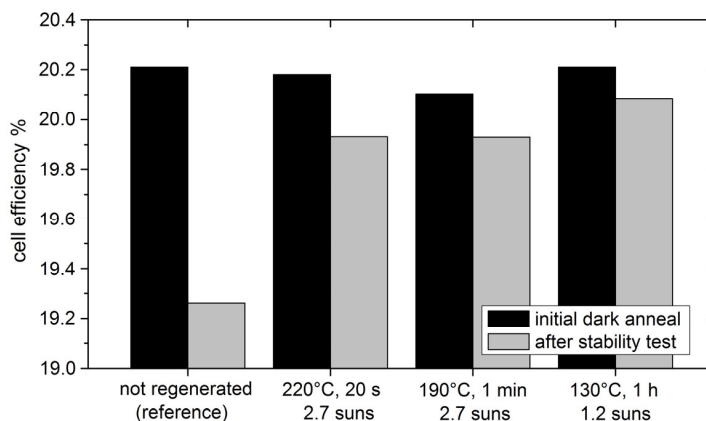


Fig. 3. Initial and stabilized absolute cell efficiencies of 2 Ωcm PERC cells regenerated at different conditions.

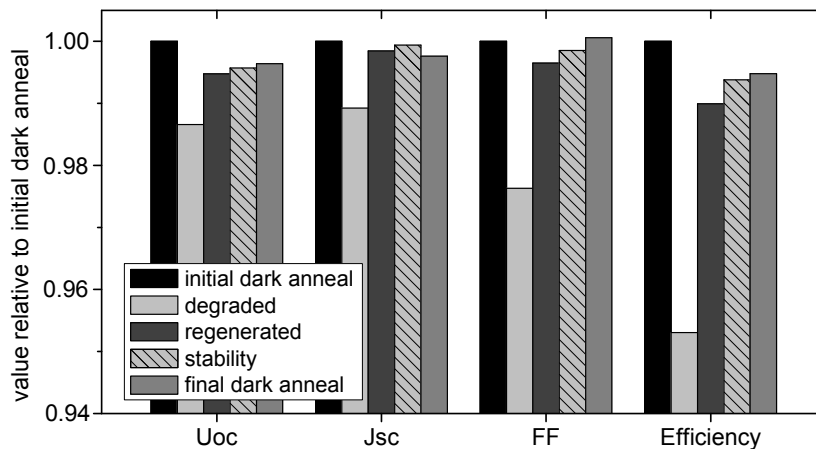


Fig. 4. Relative change of a 2 Ω cm PERC cell parameters after degradation, regeneration, stability test and final anneal (regeneration at 130°C, 1.2 suns, 1 hour).

4. Conclusion

We have shown that an adjustment of the $\text{SiN}_x\text{:H}$ passivation layer properties can be used to optimize the regeneration kinetics of boron doped Cz PERC cells. Cells with a higher presumed hydrogen release from the passivation layer into the bulk during a firing step show a reduced efficiency drop and regenerate slightly faster. Additionally, we investigated the stability of cell efficiencies after industrially applicable regeneration procedures. Even with fast regeneration steps of 20 s, stable efficiencies close to 20% can be achieved.

A combination of adjusted silicon nitride properties and a fast high temperature high illumination intensity regeneration process can thus be used to stabilize high cell efficiencies also for lower bulk resistivity materials.

Acknowledgements

The authors would like to thank all members of the departments of characterization, technology center and solar cell development at SolarWorld Innovations in Freiberg, Germany.

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